Insights from using influence diagrams to analyze precursor events

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1. Introduction

Precursor analysis, the evaluation of "near misses," has been an activity of the Nuclear Regulatory Commission for almost twenty years. One item that has remained constant over this time is that the focus of the analysis has been on modeling the scenario using a risk model and then utilizing the results of the analysis to determine the severity of the precursor incident. The investigation of precursor events can be used as a source of information for the construction of a structured methodological approach for operational decisions. This methodology, which is the focus of a research project currently underway, aims at the evaluation of the optimal strategy during a pre-core-damage incident or off-normal situation. The methodology is based on the integration of probabilistic safety assessment (PSA) and decision analysis tools such as influence diagrams/decision trees. We demonstrate this technique via an evaluation of a U.S. precursor incident.

2. The Precursor Event

To demonstrate the methodology, we make use of a precursor event that occurred 15 years ago at the Davis Besse U.S. nuclear power plant (NPP) [1]. The scenario of the event is shown in Table 1.

3. The PSA Analysis

The Probabilistic Safety Assessment (PSA) model is required to introduce plant information into the influence diagram. The first step of the PSA analysis for the loss of feedwater event is to decompose the sequence of events into blocks of times each characterized by a plant *configuration* [2]. Thus, we are discretizing the plant state into time bins, where like time bins are grouped together into a

Table 1. Loss of main feed water event.

Time	Action
0.0 min	Main Feedwater Pump (MFP) 1 trip (reactor and turbine trip a t = 30 sec)
0.5 min	Main steam isolation valve closed
6.0 min	Reactor Operator 2 (RO2) incorrectly trips SFRCS (which isolates AFW)
6.5 min	Auxiliary Feedwater (AWF) pumps trip on overspeed
7.0 min	RO2 finds error of AFW isolation
7.0 min	RO1 resets SFRCS. Since AFW isolated, it does not reset
7.5 min	RO1 open press. spray, RCS press. decreases
9.0 min	Both steam generators boil dry
9.0 min	RO1 and Senior Reactor Operator (SRO) 1 send equipment operators to restore AFW
11.0 min	RO2 sent RO1 to reset startup feedwater pump, primary PORV opens
16.0 min	RO2 and SRO2 recommend feed-and-bleed (F&B) be initiated
16.5 min	RO2 starts the startup feedwater pump into steam generator 1
18-20 min	AFW pumps align and begin to function

Table 2. Chronology the loss of MFW precursor.

Configuration	Time	Description
1	0.0 min	The nominal plant state
2	0.0 min	Loss of MFW1 pump
3	0.5 min	Plant trip and MSIV closed
4	5.0 min	Complete loss of MFW system and plant in tripped state
5	6.0 min	Loss of MFW and isolation of AFW
6	9.0 min	Both steam generators boil dry, still no MFW or AFW
7	16.5 min	Startup feedwater pump injects into steam generator 1 (no MFW/AFW)
8	19.0 min	AFW pumps align and begin to function

single bin. For the loss of feedwater event at Davis Besse, there were a total of eight relevant configurations over the period of interest, which are summarized in Table 2.

After the identification and discretization of each plant states during the incidents, each state must be evaluated using the PSA model [3]. To perform this step, the plant state during a particular configuration must be "mapped" onto the PSA model. This mapping process requires the identification of specific basic events in the PSA that are impacted by component degradations or initiating events. We identified relevant basic events for each of the configurations and adjusted the PSA accordingly. Then, for each configuration, we solved the PSA by regenerating the core damage minimal cut sets (Figure 1).

The discretization of the precursor event into configurations allows us to identify the critical points in time when major decisions need to be made, as well as the corresponding decision alternatives. These points are evident from

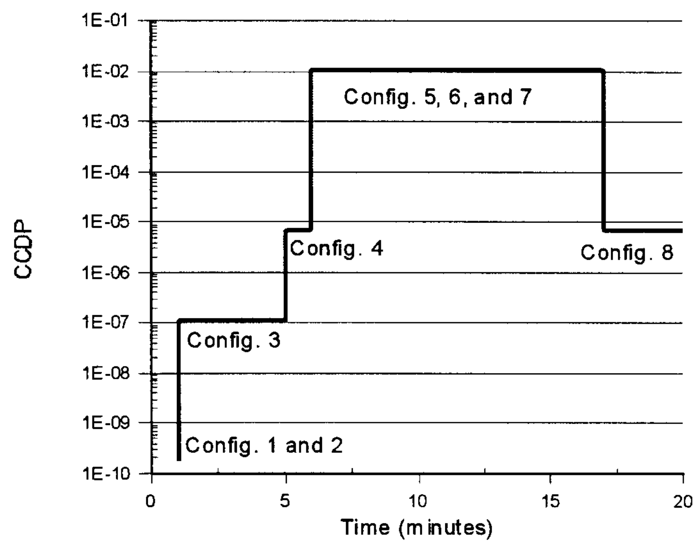

Fig. 1. CCDP for the 8 configurations of the Davis-Besse incident

the discontinuities (increases or decreases) in the CCDP. CCDP increases can correspond to a plant change in configuration due to some unexpected event or to error of implementing a previously decided strategy. CCDP decreases indicate the contrary. For the loss of main feedwater event, main discontinuities in the CCDP took place around t = 6min (5 to 7 min) and t = 9min (8 to 14 min). These two "times" coincided with the choice of manually actuate AFW and then waiting for restoration of AFW. These decision points match the two bifurcations shown in Figure 2 for the PSA event tree model. One can visualize this concept, thinking of walking on the event tree sequence as the incident progresses.

4. Influence Diagrams and the Decision Making Process

Once the main decision point and alternatives have been identified, the result of this analysis feeds the corresponding Influence Diagram (ID). The ID used to evaluate this situation must consider the sequence of decisions, and will consequently be a sequential ID [4-5]. The model used to evaluate the Davis Besse event is represented in Figure 3. The purpose of the ID is to extract information about the optimal strategy for this incident. Therefore, the accident sequence approach will be analyzed from a slightly different perspective than that adopted in human-decision reliability analysis [6].

Note that the ID contains two decisions at times 6 min and 9 min. At six minutes, the secondary reactor operator (RO2) informed the shift supervisor (SRO1) of the possibility to start AFW manually. SRO1 faced the following

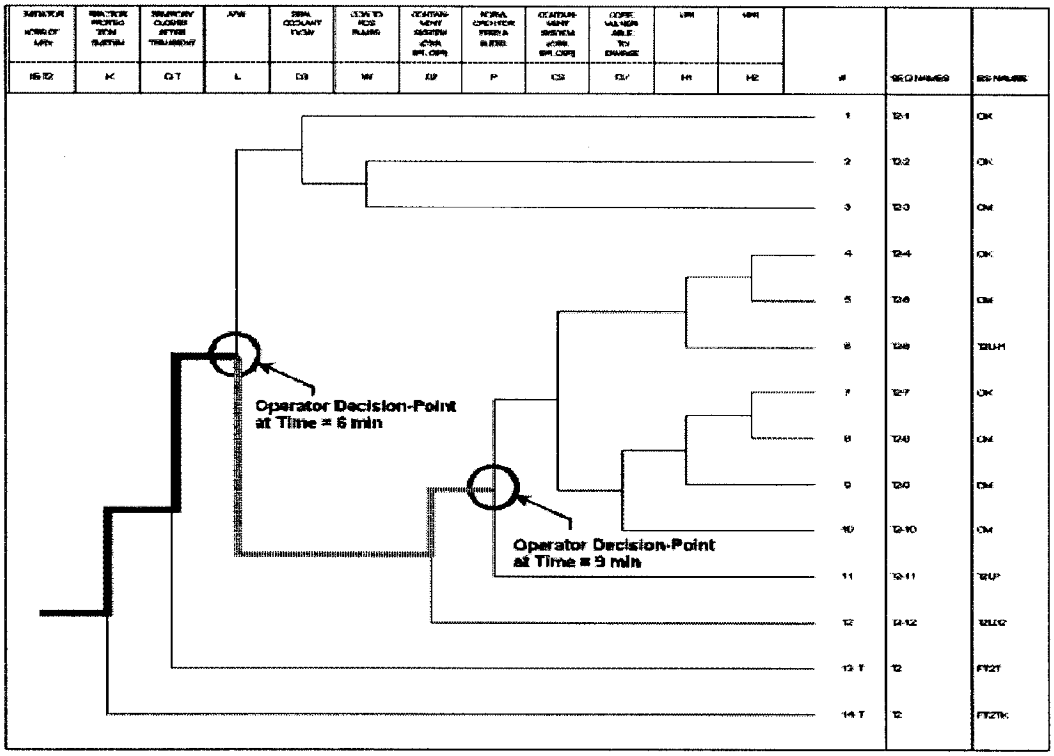

Fig. 2. The two main decisions correspond to points of risk-increase from the PSA.

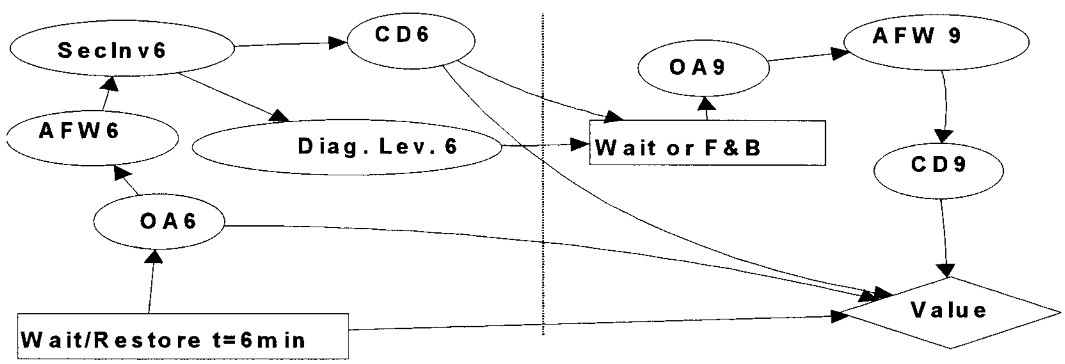

Fig. 3. ID for the Davis Besse event.

decision: "wait" or take actions to "restore AFW" (node Wait/Restore t = 6 min). AFW restoration involves some operator actions to be started (node OA6). Since it is not certain whether or not the operators will perform their actions correctly, we model the operator action (OA6) as a chance node. These actions must be analyzed using a human reliability model, e.g., [3, 7–8]. The success or failure of the operators to perform their tasks will influence the status of the AFW, which we represent via the AFW6 chance node. The next chance node is the level of water in the secondary coolant system. The coolant inventory (represented as SecInv6) affects the core status and must be checked by the supervisor ("Diag. Lev. 6" chance node).

At this point, we can summarize the sequence of events that could lead us to core damage (node CD6) using the CCDP for the corresponding plant configuration (see Figure 2). The second part of the ID represent the decision and events after time t = 9 min and is similar to the first part, with the remark that the decision at t = 9 min is to either "wait and see if the AFW system can be restored" or to "go directly to F&B operations."

5. Best Strategy Evaluation

Once the PSA analysis is complete and is incorporated into the influence diagram (and corresponding decision tree), we can evaluate the "best" strategy for this precursor incident. We must now establish the criterion of a best strategy. The decision analysis framework in which we have inserted the precursor event can enable us to evaluate the strategy from different perspectives that range from the economic point of view to the solely safety-related one. For our trial study, we focused primarily on safety, specifically by utilizing a non-dimensional metric on the potential for core damage. Thus, we used a simple utility function that can take on one of two values, -1 if we have core damage and $+1$ if we avoid core damage. Using this, we found the results shown in Table 3.

The results shown in Table 3 indicate that, based on our model, at 6 minutes the best decision would have been to wait for the automatic actuation of AFW. Then at 9 minutes, the operators should have chosen to go to F&B if AWF was not available. In reality the operators chose to actuate AFW manually, thinking of the advantage of a higher inventory level. Later in the sequence, they tried to avoid going to F&B, presumably not to expose the plant to unnecessary challenges.

Table 3. The "best" decisions from the Davis-Besse precursor analysis.

Time	Best Decision
6 minutes	Wait for automatic actuation of AFW
9 minutes	Go directly to F&B

6. Conclusions

We have presented an approach for evaluating the decision-making process during precursor incidents. This approach is the first step in the construction of a methodology which is based on the incorporation of the insights and quantification of PSA analysis into decision-analysis tools such as influence diagrams. The methodology aims at enabling an on-line formal evaluation of the decisions that are to be taken during an off-normal event.

Our work has shown that PSA is well suited for determining decision alternatives and indicating where, in a sequence of unfavorable events, critical decisions are to be made. We have shown that it is possible to account for the evolution of the risk during the incident through re-evaluation of the PSA model for relevant configurations. CCDP becomes an essential element in the evaluation of the best strategy and the bridge to the use of formal decision-analysis tools. These tools, in their turn, provide the formal framework for a strategy evaluation that is not solely based on engineering judgment. It is planned to further this research by looking at potential operational events, thus turning the analysis to a predictive mode. The final goal of the research is the construction of a prototype software tool for on-line decision making for the management of operational incidents.

7. Acknowledgments

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